PULSE SHARPENING WITH METAL-OXIDE BULK SWITCHING DEVICES

by

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ABSTRACT

Certain niobium oxide (NbO_x, $x \approx 2$) materials are near insulating at room temperature but undergo an "insulator-to-metal" transition near 800°C. A similar transition can be initiated at room temperature by applying an electric field exceeding the "threshold" value, which depends on the oxygen concentration (x) of the NbO_x. Metal-oxide threshold switch (MOTS) prototypes are obtained by applying appropriate contacts and packaging. Threshold voltages range from 100 V to several kV. A typical MOTS has a surge current capability exceeding 100 A, an off-state capacitance of only a few pF, and a switch delay of less than 0.5 ns. The latter two characteristics make the MOTS potentially superior to conventional devices for a number of high-speed, high-current switching functions. In particular, insertion of a MOTS into the output circuit of a conventional pulse generator can "sharpen" the leading edge of the pulse to yield a ns or even sub-ns risetime.

Introduction

The physical mechanism for the sub-nanosecond threshold switching from high to low resistivity and the subsequent high current regime in NbO_x ($x \approx 2$) and certain other transition metal oxides[1] is still under study and will be the subject of a future publication. There are, however, a few preliminary empirical conclusions and rules which can facilitate understanding and using the new metal oxide threshold switch (MOTS); namely, (1) contacts are non-rectifying and characteristics are essentially symmetrical; the switching is based on a true "bulk" effect, leading to formation of a current carrying filament in the "on" mode; (2) the filament is probably not as narrow and not as hot as previously assumed, in agreement with a model proposed by Adler[2] for threshold switching in another material; (3) threshold voltage is determined by the thickness of the switching material, but also by the deviation from stoichiometry in NbO_x ($x \approx 2$), and by doping; these two influences will reduce threshold field, but also off-state resistivity; (4) after cessation of the high current pulse, the material reverts to the high resistance state within a few μs; this observation is compatible with a purely electronic model of switching involving deep traps, and with a thermal model as well; (5) NbO_x off state resistances (ranging from 1 kilohm to megohm for typical MOTS) and threshold voltages (ranging from $\approx$ 100 V to several kV) decrease with increasing temperature from

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room temperature up, in correspondence with an activation energy of ≈ 0.8 eV, which is also indicated by optical transmission measurement;[3] (6) polycrystalline as well as single crystal NbO_x material exhibits sub-nanosecond high current switching.

All these observations are apparently compatible with the model of a trap dominated semiconductor for NbO_x ($x \approx 2$), although others are being considered.[4] In any event, physical properties and characteristics as discussed below are based strictly on empirical behavior, verified may times, and are thought sufficient to begin work on applications such as pulse sharpening.

Physical Construction of MOTS Prototypes

As in most solid state devices, construction centers about a "chip." Small (1 x 1 x 0.5 mm) chips of single crystal niobium monoxide were used extensively for materials with low threshold voltages (V_{th} = 80...800 V) as required for transient suppressor applications.[1,5] Thin polycrystalline NbO_x ($x \approx 2$) layers were thermally grown on the NbO chips (the NbO is a semiconductor and also acted as "bottom" electrode). However, relatively large single crystal chips, or "wafers" (5 mm diameter, 0.5 mm thick) proved more feasible for applications requiring high V_{th} values. These values are predetermined by wafer thickness and oxygen content (x), and by dopants. Most chips and wafers were provided by Yeshiva University, New York City.[1]

A variety of contacts has been successfully used in NbO_x MOTS prototypes, such as pressure contacts of tungsten, niobium and graphite, and deposited contacts of niobium and aluminum. The original low voltage chips were often contacted by niobium tape formed into a loop which served as a low inductance wide area pressure contact. Both parts were inserted into standard 1 N23 microwave packages. A larger low inductance package is being developed for high voltage applications. While all tested contacts are essentially non-rectifying, it is necessary that they be of low resistance. In the high current mode of the MOTS, a substantial voltage drop may occur, a contact having tens of ohms causing arcing and arc erosion.

Characteristic Pulse Response of MOTS

In the following discussion it is assumed that "clean" impedance matched systems are used and the influences of parasitic impedances are minimized. The authors generally used 50 ohm components connected by appropriate coaxial cables. If the small (a few pF) capacitance, C_o, of the MOTS in its low current state is ignored, the initial pulse current is given by the leakage resistance R_o of the MOTS. The right-most curve in Figure 1 shows the response of a typical device to an applied pulse with 1 ns risetime. As the applied voltage increases, the corresponding current increases becoming more "superlinear," until the V-I curve assumes an infinite slope. The first phase of switching is completed at this moment; the threshold voltage has been reached and further increases in the applied voltage have little effect on the device voltage ("clamping"), but device voltage begins to drop rapidly to the "holding

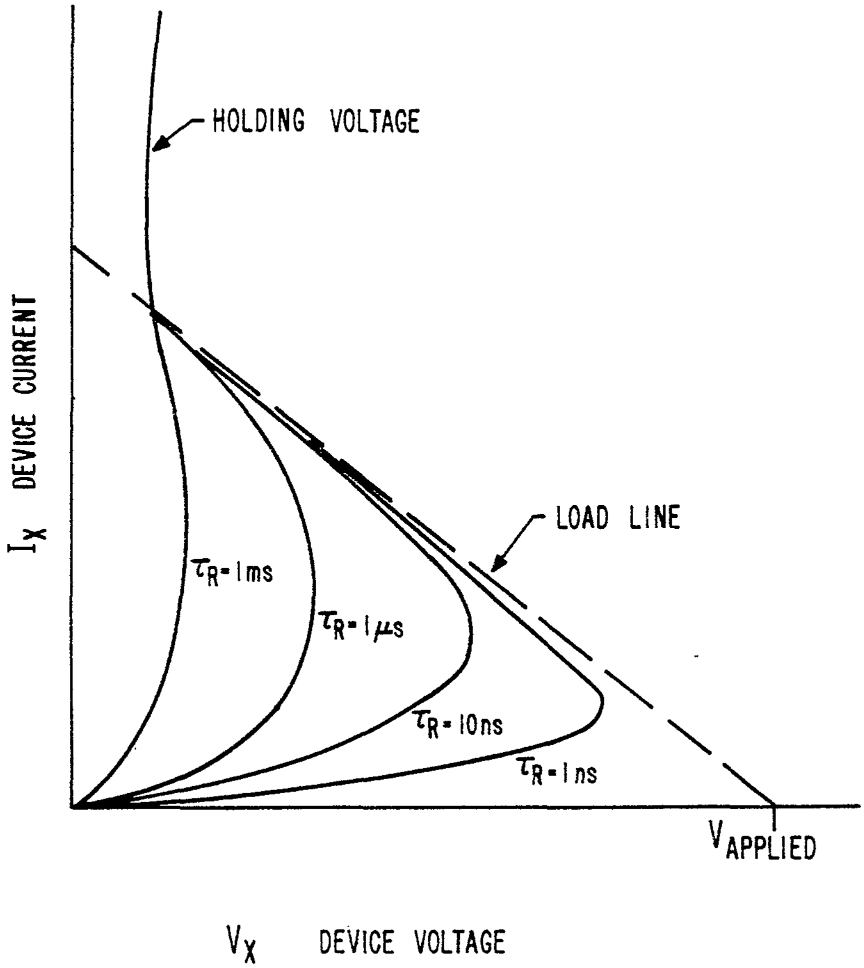


Figure 1. MOTS response to pulses of various risetimes, $_R$

voltage" (typically 20 V). Then, the MOTS essentially acts as a short, and the current is given by the final applied voltage (minus the holding voltage) and the load line (25 ohm in a 50 ohm transmission line system) Most of the increase in current after reaching the peak, or "threshold" voltage occurs in ≈ 5 ns. The I-V curves of Figure 1 are not time-independent characteristics but rather descriptions of the device response to various pulses. Figure 1 shows this schematically. The applied voltage needed to switch, and the device peak voltage are much less when a pulse with τ_R = 1 μs risetime is applied than in the case of a 1 ns risetime. Also, a long pulse of any shape can cause delayed switching at a relatively low voltage. If a MOTS is connected to a conventional diode "curve tracer," the device peak voltage may not exceed by much the holding voltage (τ_R = 1 ms curve of Figure 1). Conversely, a pulse with a risetime of 0.5 ns or less risetime will produce a device voltage peak higher than the one shown by the τ_R = 1 ns curve of Figure 1. Such pulses, however, are difficult to generate, propagate and observe, and the authors used pulses with 1 ns risetime and 1 ns duration and an oscilloscope with 0.7 μs resolution to determine "threshold voltage" (V_{th}).[1] The MOTS response to pulses of various risetimes probably reflects the energy which must be accumulated for the nucleation, and subsequent, expansion of a current filament to its saturation value. After termination of the pulse, when the MOTS no longer receives energy, the accumulated energy (filling of traps and/or heating) dissipates, as demonstrated in the authors' double-pulse experiments; a "standard" 1 ns "search" pulse was applied to probe the threshold voltage after the cessation of the first (1 μs) pulse. In a typical case, it took approximately 6 μs for V_{th} to recover most of its previous value.

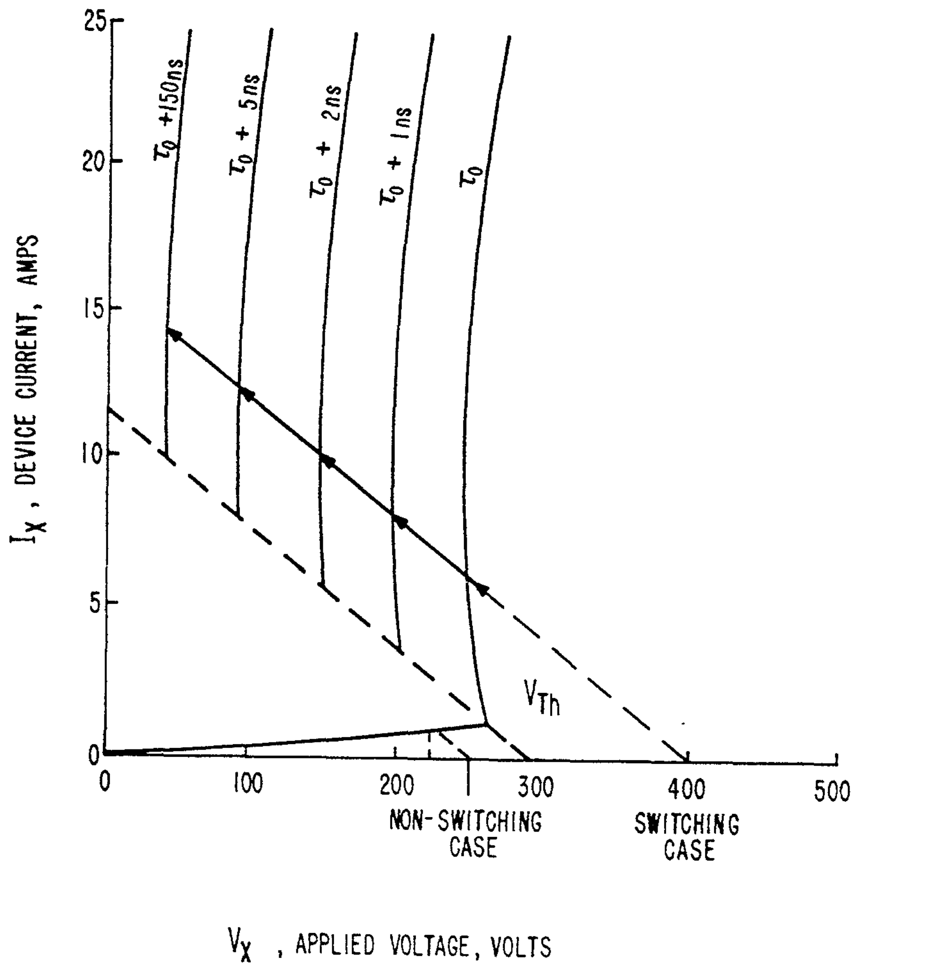
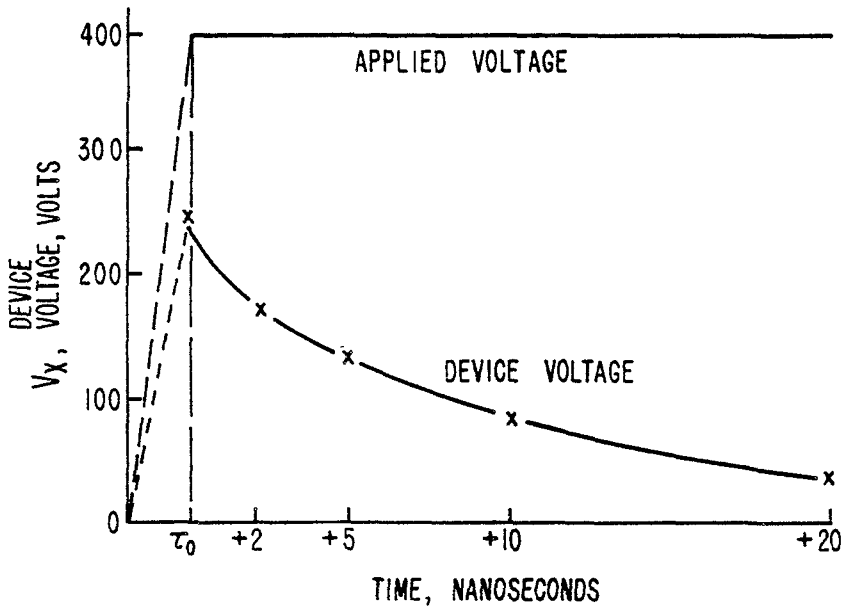


Figure 2. Post-switching MOTS currents as function of applied voltage and of time.

Figure 2 illustrates the influence of the maximum applied pulse voltage on the switching of the MOTS, again assuming a 50 ohm system an a 1 ns risetime pulse and an oscilloscope of 0.7 ns resolution to obser device voltage and current. The applied voltage must be minimally 300 to provide switching within fractions of a ns; part of this voltage is drop caused by the preswitching leakage current through the load line, the remaining 280 V being the threshold voltage. A lower applied voltage will not cause immediate switching but may lead to "delayed" switching for a sufficiently long pulse, as explained above. For a higher applied voltage, the device voltage remains essentially "clamped" to the threshold voltage and then drops to the holding voltage, but at a higher current. Analogously, post switching changes of the applied voltage, unless it goes below the holding value, have little influence on the device voltage. The MOTS in the high current mode acts as a "dynamic short." At the same time, the power absorbed by the MOTS during high current operation is kept small by the smallness of the voltage drop. Currents to 250 A have been sustained.



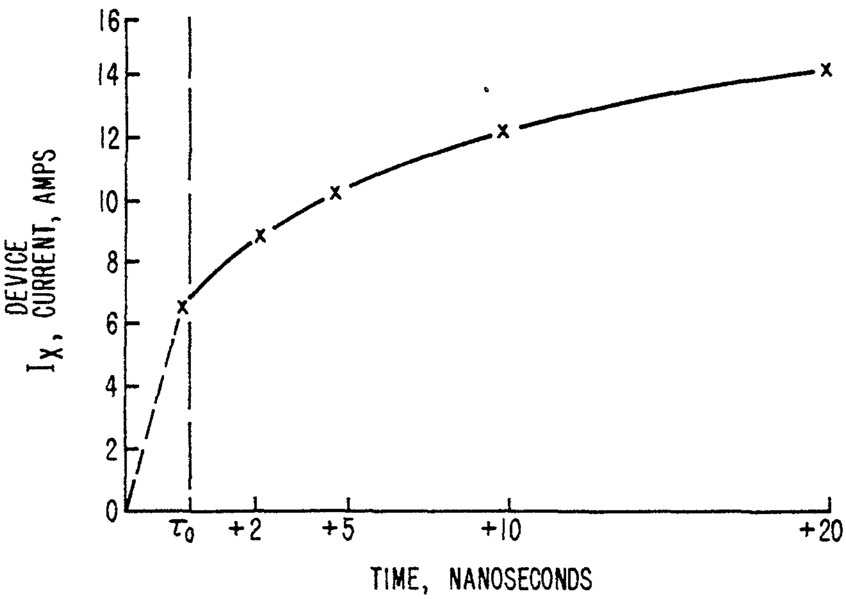


Figure 3. MOTS response to 1 ns risetime pulse from 50 ohm transmission line with 50 ohm termination.

Figure 3 demonstrates the measured response of a typical MOTS to pulses with τ_R = 1 ns risetime. The MOTS is in the transient suppressor mode parallel with the 50 ohm line termination.[1] The current increase is more rapid in this "pulse sharpening" mode discussed below.

Because of attractive MOTS features, such as compactness, fast response, and high surge current capability, the authors decided to test the effectiveness of then available low voltage MOTS prototypes as "pul sharpeners." The device was inserted into the circuit shown on Figure 4 (without the "cable pulser" and the connections indicated by dashed lin

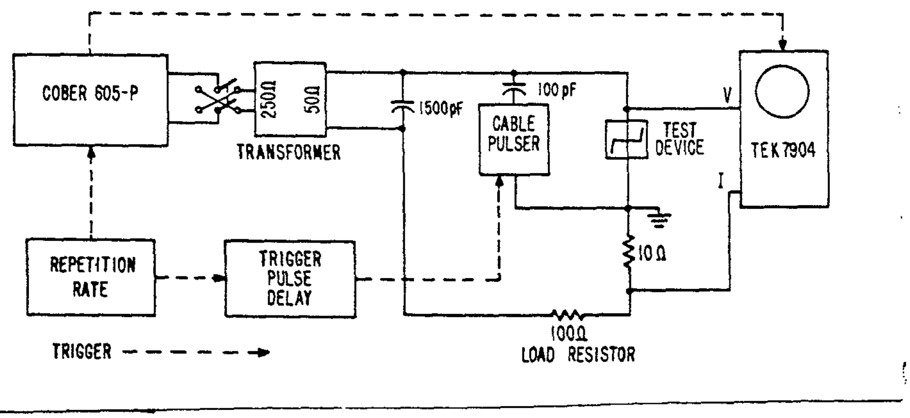


Figure 4. Test of MOTS prototype for improving risetime of pulse current I. Trigger circuit (dashed) suppresses jitter.

The Cober pulse generator was set to generate a slow risetime (≈ 150 ns applied voltage, which is reflected by a similar current when the MOTS i replaced by a short. With the MOTS in series with the pulser output, th risetime of a 2.5 kV, 20 A pulse was reduced from 150 to 2 ns. Pulse repetition rates to 10 kHz were applied at smaller currents. Superimposing a fast rising "trigger" pulse to the MOTS virtually eliminated time jitter of the "sharpened" periodic pulses (full test circuit of Figure 4

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